# Antiproton Production in $pp, dp$ and $dd$ Collisions close to Threshold [*]

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**Abstract**

The production of antiprotons in $pp$ collisions is investigated close to threshold where experimental data about the total cross section are not available. We analyze the latter reaction within the LUND string model for inclusive $\bar{p}$ production and within the framework of a one-boson exchange model for the exclusive reaction $pp \rightarrow ppp\bar{p}$. The application of our new results to the analysis of subthreshold antiproton production in $d+p$ and $d+d$ collisions shows cross sections that are much lower than expected before. Nevertheless, the comparison of experimental $\bar{p}$ differential cross sections from $d+p$ and $d+d$ is expected to provide valuable information about a nonnucleonic component in the deuteronwavefunction.

The production of particles at energies below the free nucleon- nucleon threshold is one of the most promising sources of information about the properties of nuclear matter at high densities or about nucleon-nucleon correlations at short $N - N$ distances [1]. Apart from heavy meson $(\eta, K^+, K^-, \rho, \omega, \Phi)$ production, the investigation of antiprotons is of particular interest since they involve a much larger production threshold and can be more easily identified with magnetic spectrometers due to their large mass and negative charge. In fact, antiprotons have been detected at far subthreshold energies in both, p + A and A + A collisions [2, 3, 4, 5, 6]. The actual magnitude of the cross sections observed indicate strong in-medium modifications of the antiprotons as found from independent transport theoretical studies [7, 8, 9, 10]. Although the proper magnitude of the $\bar{p}$ potential and its annihilation cross section in the medium is still a matter of debate, it is clear that the dominant production mechanism in nucleus-nucleus collisions proceeds via intermediate baryon resonances since the latter act as short-time energy reservoirs for the $\bar{p}$ production [8, 10, 11]. On the other hand the $N\Delta$ or even $\Delta\Delta$ channels play a minor role in proton-nucleus and deuteron-nucleus reactions since the resonances on average decay before colliding with another nucleon due to the much lower densities involved [12].

However, the poor knowledge of the elementary production cross section $pp \rightarrow \bar{p}+X$ especially close to threshold leads to large ambiguities in the interpretation of the experimental data about subthreshold $\bar{p}$ production in p + A and A + A collisions and thus to sizeable uncertainties for the antiproton potential or selfenergy in the nucleus. It is thus mandatory to analyse the elementary production in situations where the kinematical conditions are more clearly defined and where in-medium potentials as well as intermediate pion induced production channels as well as antiproton annihilation can approximately be neglected. This is clearly the case for $pp$ collisions and also quite well fulfilled for $d + p$ and $d + d$ reactions according to the analysis in [12, 13].

In this paper we thus concentrate first on the inclusive process $pp \rightarrow \bar{p}X$, which in comparison to the data from [14] is quite well described within the LUND string formation and fragmentation model [15] at invariant energies above $\sqrt{s} \approx 4.7$ GeV. Within the same approach we then compute the cross section for the exclusive reaction $pp \rightarrow ppp\bar{p}$ which due to kinematical reasons is equal to the inclusive cross section close to threshold. The latter exclusive channel, furthermore, is described by using i) a constant matrix element and ii) matrix elements calculated within the framework of the one-boson exchange model where coupling constants and formfactors are fitted to other related cross sections. The sensitivity of the antiproton spectra in subthreshold $d - p$, $d - d$ collisions then is reanalyzed in particular with respect to a non-nucleonic component in the deuteron wave function (cf. ref. [13, 16]).

We start with the inclusive $\bar{p}$ production in $pp$ collisions and show in Fig. 1a) the available experimental data from [14] (full squares) in comparison to the results from the LUND string model (LSM) [15] (open circles) as a function of the invariant energy above threshold. Since the description of the inclusive data within the LSM is quite good, we use the same approach to compute the relative fraction of events corresponding to the exclusive channel $pp \to ppp\bar{p}$ which is represented in Fig. 1a) by the crosses. Whereas at higher energies the inclusive antiproton production corresponds to events with 3 baryons and further mesons, below about $\sqrt{s} - 4m \approx 0.4$ GeV the dominant channel is $pp \to ppp\bar{p}$. It should be noted that the LSM at this energy predicts cross sections well below the parametrization from Batko et al. [17] (dashed line in Fig. 1b), however, it is not clear if the LSM should provide reasonable extrapolations closer to threshold. We thus have to employ a microscopic model for the latter exclusive channel to obtain information about the cross section closer to threshold.

For this purpose we analyze the process $pp \to \bar{p}ppp$ within the framework of the one-boson-exchange (OBE) model according to the diagram in Fig. 2 describing the $\bar{p}p$ production via the off-shell production of $\pi^0, \rho^0$ and $\omega$ pairs that annihilate to a $\bar{p}p$ pair. The general expression for this cross section (denoted by $\sigma_4$) can be written in the form:

$$\sigma_4 = \frac{1}{128(2\pi)^5 \lambda(s, m^2, m^2)} \int_{m^2}^{s_3^+} ds_3 \int_{t_3^-}^{t_3^+} dt_3 \int_{t_1^-}^{t_1^+} dt_1 \int_{s_2^-}^{s_2^+} ds_2 \int_{t_2^-}^{t_2^+} \tag{1}$$

$$| T_{NN \to \bar{p}pNN}(t_1, t_2, t_3, s_2) |^2 \frac{dt_2}{\lambda^{1/2}(s_2, t_3, t_1)\lambda^{1/2}(s_3, t_3, m^2)}$$

where the following notations are introduced : $\lambda^{1/2}(x, y, z) = (x - (y^{1/2} + z^{1/2})^2)^{1/2}(x - (y^{1/2} - z^{1/2})^2)^{1/2}$ if $y^{1/2} \geq 0$ and $z^{1/2} \geq 0$ ; $t_1$ and $t_3$ are the transfers from the initial nucleon to the final one corresponding to the upper and lower verticies of the graph in Fig. 2, respectively, or the squares of the four- momenta of the exchanged mesons in the intermediate state ; $t_2$ is the transfer from the intermediate meson to the final antiproton; $s_2 = m_{\bar{p}p}^2$ is the square of the effective mass of the $\bar{p}p$ pair, and $s_3 = (p_{mes.} + p_N)^2$, $p_{mes.}$, $p_N$ are the four-momenta of the intermediate meson and the initial nucleon $N$;

$$s_3^+ = (s^{1/2} - m)^2;$$

$$t_1^\pm = 2m^2 - \frac{1}{2s_3}(s_3 + m^2 - t_3)(s_3 + m^2 - s_2) \mp \lambda^{1/2}(s_3, m^2, t_3)\lambda^{1/2}(s_3, m^2, s_2));$$

$$t_2^\pm = t_1 + m^2 - \frac{1}{2s_2}(s_2 + t_1 - t_3)s_2 \mp \lambda^{1/2}(s_2, t_1, t_3)\lambda^{1/2}(s_2, m^2, m^2));$$

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$$s_2^{\pm} = s_3 + m^2 - \frac{1}{2m^2}(s_3 + m^2 - t_3)(2m^2 - t_1) \mp \lambda^{1/2}(s_3, m^2, t_3)\lambda^{1/2}(t_1, m^2, m^2);$$

$$s_2^{min} = max(s_2^-, 4m^2)$$

$$t_3^{\pm} = 2m^2 - \frac{1}{2s}s(s + m^2 - s_3) \mp \lambda^{1/2}(s, m^2, m^2)\lambda^{1/2}(s, m^2, s_3)).$$

The matrix element $T_{NN \to \bar{p}pNN}(t_1, t_2, t_3, s_2)$ can be calculated within the framework of the one-meson exchange model taking into account both pseudoscalar, scalar and vector mesons [18]. Neglecting the higher order terms in $t^2/m^4$ caused by the tensor part of the $NN\rho$-vertex, which is legitimate at not too large transfers $t_1$ and $t_3$ (cf. [18, 19]), it can be written in the form:

$$| T_{NN \to \bar{p}pNN}(t_1, t_2, t_3, s_2) |^2 = \sum_i \frac{g_{iNN}^2 \mid t_1 \mid F_i^2(t_1)}{(t_1 - m_i^2)^2} \frac{g_{iNN}^2 \mid t_3 \mid F_i^2(t_3)}{(t_3 - m_i^2)^2}$$
$$\mid f_{ii \to \bar{p}p}(s_2, t_2) \mid^2, \qquad (2)$$

where $f_{ii \to \bar{p}p}(s_2, t_2)$ is the amplitude for the process $ii \to \bar{p}p$ and the index $i$ stands for the exchanged meson (cf. Fig. 2) while $F_i$ is the corresponding formfactor and $g_{iNN}$ is the $iNN$ coupling constant corresponding to the exchanged meson ($i = \pi^0, \rho^0, \omega$). The coupling constants and formfactors are taken from refs. [18, 19, 20].

We incoherently sum the contributions of the $\pi^0, \rho^0, \omega$-exchange graphs (cf. Fig. 2) because the amplitudes for the processes $ii \to \bar{p}ppp$ are not known sufficiently well and more reliable theoretical approaches are not available so far. Furthermore, assuming off-mass shell effects in the amplitudes $f_{ii \to \bar{p}p}(s_2, t_2)$ to be small, they can be related to the differential cross sections of the reactions $ii \to \bar{p}p$ by

$$| f_{ii \to \bar{p}p}(t_1, t_2, s_2) |^2 = 16\pi\lambda(s_2, m_i^2, m_i^2)\frac{d\sigma_{ii \to \bar{p}p}}{dt_2}(s_2, t_2). \qquad (3)$$

The latter can be written in the form:

$$\frac{d\sigma_{ii \to \bar{p}p}}{dt_2} = \sigma_{ii \to \bar{p}p}(s_2)\phi(t_2), \qquad (4)$$

where $\sigma_{ii \to \bar{p}p}(s_2)$ is the cross section for the production of the $\bar{p}p$ pair in the annihilation of the mesons of type $i$ ($\pi, \rho, \omega$, etc.). In (4) $\phi(t_2)$ is a function normalized to 1 that determines the $t_2$-dependence of the differential cross section $d\sigma_{ii \to \bar{p}p}/dt_2$. In our actual computation it was choosen to be of exponential form

$$\phi(t_2) = C_1 exp(Bt_2), \qquad (5)$$

where the constant $C_1$ is determined by the normalization of $\phi(t_2)$ and $B \approx 6 - 9$ $GeV^2$. We note that our results for the total $\bar{p}$ cross section will be without noticable

sensitivity to the actual value of B in the threshold regime where the cross section is dominated by phase space (see below).

In order to calculate $\sigma_{ii \to \bar{p}p}(s_2)$ we address to the experimental data for the cross section $\sigma_{\bar{p}p \to \pi^- \pi^+, \rho^0 \rho^0}$ [21] which can be related to the cross section $\sigma_{\pi^- \pi^+ \to \bar{p}p}(s_2)$ or $\sigma_{\rho^0 \rho^0 \to \bar{p}p}(s_2)$ using the detailed balance principle[1]. The $s_2$-dependence of the $\pi^+ \pi^-$ cross section now can be approximated by the following expression:

$$\sigma_{\pi^- \pi^+ \to \bar{p}p}(s_2) = C^2 \frac{M^4 (\hbar c)^2}{2 s_2 (s_2 - M^2)^2 + M^2 \Gamma^2)} (1 - 4m^2/s_2)^{1/2} \tag{6}$$

with $C^2 = 1, M = 2.07 GeV, \Gamma = 0.6 GeV, (\hbar c)^2 = 0.389380\ (GeV^2 mb)$.

For the calculation of the cross section $\sigma_{\rho^0 \rho^0 \to \bar{p}p}(s_2)$ the functional form (6) was taken, too, but the factor $C^2 (\approx 0.25)$ was fitted to the 3 data points available from ref. [21]. The cross section $\sigma_{\omega\omega \to \bar{p}p}(s_2)$, furthermore, was assumed to be the same as for the process $\rho^0 \rho^0 \to \bar{p}p$ since there are no data available.

Within the rather drastic approximations described above the antiproton cross section then only depends on the meson formfactors and meson-nucleon-nucleon coupling constants. In line with [18] the meson formfactors $F_i(t)$ are taken to be of monopole form, i.e.:

$$F_i(t) = \frac{\Lambda_i^2}{\Lambda_i^2 + |t_{1,3}|^2} \tag{7}$$

involving a cut-off parameter $\Lambda_i$. The actual parameters used are: $\Lambda_\pi = 0.7$ GeV/c, $\Lambda_\rho$ = 2.0 GeV/c, $\Lambda_\omega$= 1.5 GeV/c, $g_{\pi NN}^2/4\pi = 14.7$, $g_{\rho NN}^2/4\pi = 40.8$ and $g_{\omega NN}^2/4\pi = 20$ [18, 19]; the values for $\Lambda_\pi, g_{\pi NN}^2$ were taken from [20] where they were found to yield a good description of $\pi - N$ scattering. Note, that the cut-off parameters $\Lambda_i$ and the coupling constants $g_{iNN}$ for $\rho$- and $\omega$-mesons correspond to the relativistic (energy-independent) one-boson -exchange potential as considered in ref. [18, 19].

Calculating the cross section $\sigma_4$ (1) as a function of $\sqrt{s}$ within the parameters specified above we obtain the solid line in Fig. 1a) that describes very well the cross section for the exclusive channel from the LSM above $\sqrt{s} - 4m \approx 0.5$ GeV. The dotted line in Fig. 1a) shows the result when including only $\pi^0$ exchange which, however, is suppressed as compared to the vector meson exchange contributions due to the lower restmass and cut-off parameter. Qualitatively, a similar result was found for $p\bar{p}$ production from meson-meson annihilation in ref. [22].

One might worry about the validity of the boson exchange model for the $p\bar{p}$ production close to threshold. In this respect we additionally employ a simple phase-space

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[1]A similar concept has been used by Ko and Ge in ref. [22], where the authors study the $p\bar{p}$ production by $\pi\pi, \eta\eta, \rho\rho$ and $\omega\omega$ channels in a hot fireball.

model assuming that the $\bar{p}$ cross section is proportional to the 4-body phase-space integral $R_4(\sqrt{s}, m, m, m, m_{\bar{p}})$ [14] with a constant fitted to the first experimental point at $\sqrt{s} - 4m \approx 1$ GeV. The result of this simple approximation is displayed in Fig. 1b) by the dotted line and practically coincides with the result from the OBE model up to $\sqrt{s} - 4m \approx 0.7$ GeV. Thus the $\bar{p}$ cross section close to threshold appears to be dominated by phase space, only. Now combining the results for the antiproton cross section from the OBE model and LSM in their respective kinematical regimes, we can use these cross sections for further applications in p + A and A + A reactions. We note that a good fit for the inclusive $\bar{p}$ cross section is given by

$$\sigma_{pp \to \bar{p}+X}(\sqrt{s}) \approx R_4(\sqrt{s}, m, m, m, m_{\bar{p}}) \ \frac{D}{4((\sqrt{s} - 4m)^2 + \Gamma^2/4)} \ [mb] \qquad (8)$$

with $D = 4 * 10^{-3}$ and $\Gamma = 3$ GeV (solid line in Fig. 1b).

There is a chance that final state interactions might increase again the $\bar{p}$ yield very close to threshold, but experiences with $\eta$ production in $pp$ collisions indicate that a respective enhancement is limited to the energy range $\sqrt{s} - 4m \leq 40$ MeV [23].

Before exploring the consequences for $\bar{p}$ cross sections in subthreshold hadron-nucleus and nucleus-nucleus reactions employing our new 'elementary' cross section, we consider the reactions $d + p$ and $d + d$ where medium effects can approximately be neglected as discussed above. Recently, these reactions were studied [13] to extract some new information about the nuclear structure at short $N - N$ distances employing the extrapolation from Batko et al. [17]. Since the latter cross section now sizeably overestimates our new results by more than an order of magnitude close to threshold (cf. Fig. 1b) the sensitivity of the Lorentz invariant $\bar{p}$ cross section due a non-nucleonic component in the deuteron wavefunction has to be reexamined.

Our model for antiproton production in $d + p$ and $d + d$ is described in detail in ref. [13] and doesn't have to be repeated here. The only modification introduced is to replace the parametrized form of the elementary $\bar{p}$ cross section by our new results (8). The deuteron wavefunction (d.w.f.) employed is that obtained from the Paris potential [24] transformed to a relativistic version that only depends on the light cone variable $x$ and the transverse momentum $k_t$ (cf. [16]). The results of our calculation (with the Paris d.w.f.) for the Lorentz invariant cross section $E_{\bar{p}} d^3\sigma/dp_{\bar{p}}^3(\sqrt{s})$ at $0^0$ in the laboratory system for $d + p$ at a deuteron momentum of 10 GeV/c and $d + d$ at 7 GeV/c are displayed in Fig. 3 within the parametrization from Batko et al. [17] (solid lines) and our new cross section (dashed lines), respectively[2]. Whereas the reduction of the cross section in the $(d + p)$ case with the new cross section is already about a

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[2]In [13] for the calculation of the $\bar{p}$ spectra in the $dp \to \bar{p}X$ reaction a factor $4\pi$ was missing in the normalization of the d.w.f.

factor of 7, the $(d + d\,)$ cross section decreases up to a factor of 36. The maximum in the differential cross section for $(d + d)$ of about 7 $pb\ c^3/GeV^2$ at $P_d = 7$ GeV/c now will be hard to measure experimentally.

We follow ref. [13] and additionally consider the possibility that the deuteron has a 3% admixture of a non-nucleonic component as described by Eqs. (5) - (8) in [13] in line with refs. [16, 25]. The result for the Lorentz invariant $\bar{p}$ cross section in this case is also shown in Fig. 3 using the extrapolation from Batko et al. [17] (dot-dashed lines) and our new 'elementary' cross section (dotted lines). Here we find a very pronounced enhancement of the $\bar{p}$ yield when including the non-nucleonic component; the relative enhancement is even larger for the new cross section than for the parametization used previously. Thus by measuring antiproton production in $pp$ collisions and comparing relative to the $d + p$ reaction the existence of a non-nucleonic component or its relative strength should be clearly measurable.

In ref. [13] it was, furthermore, suggested that the ratio of the antiproton cross section from $d+d$ to $d+p$ reactions might provide some information on the non-nucleonic component of the d.w.f. itself because ratios of cross sections are less sensitive to the actual magnitude of the elementary cross section. In fact, within the parametrization from ref. [13] a relative sensitivity up to a factor of 1.5 - 2 has been found (cf. Fig. 3 of [13]). Our reanalysis of this suggestion with the new 'elementary' cross section is shown in Fig. 4 for a deuteron momentum of 9.5 GeV/c. Here the solid line reflects a calculation including a 3% admixture of the non-nucleonic component while the dashed line is obtained with the Paris d.w.f., only. Contrary to ref. [13] we find that the relative ratio $dd/dp$ changes only slightly with the $\bar{p}$ momentum such that the ratio itself does no longer qualify for determining the deuteron structure.

In summary, we have reexamined the production of antiprotons in $pp$, $dp$ and $dd$ reactions close to threshold energies. Our results are based on a combined analysis within the LUND string model [15], an effective OBE model for the exclusive channel as well as on 4-body phase space and clearly indicate that the estimates for $\bar{p}$ production at subtreshold energies in p + A and A + A collisions within the extrapolation of Batko et al. [17] are severely overestimated. In $d+p$ reactions at 10 GeV/c the relative reduction is about a factor of 7 whereas in $d + d$ collisions at 7 GeV/c we find a reduction by a factor of about 36 as compared to previous estimates. These reduced cross sections, on the other hand, will require much more attractive antiproton selfenergies in the nuclear medium than estimated before in p + A and A + A reactions.

The comparison of $pp$, $dp$ and $dd$ collisions will, however, still provide valuable information about a non-nucleonic component of the deuteron wavefunction itself. Contrary to our previous analysis [13] the $dd/dp$ ratio is no longer promising in this respect. The

next step in the clarification of this problem is clearly related to experimental data that e.g. can be taken at KEK.

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# Figure Captions

**Fig. 1:** The antiproton cross section as a function of the invariant energy above threshold $\sqrt{s} - 4m$. a) The open circles represent the results from the LUND string model (LSM) [15] in comparison to the experimental data for the inclusive production [14] (full squares). The crosses represent the results from the LSM for the exclusive channel $pp \rightarrow ppp\bar{p}$ and the solid line is the result from the one-boson-exchange (OBE) model described in the text including $\rho^0$, $\omega$, and $\pi^0$ exchange while the dotted line stands for the $\pi^0$ exchange contribution, only.
b) The phase-space model - including only the integrated 4-body phase space - is displayed by the dotted line and practically coincides with the result from the OBE model up to $\sqrt{s} - 4m \approx 0.7$ GeV. The solid line represents the fit from eq. (8) while the dashed line shows the approximation from Batko et al. [17].

**Fig. 2:** The one-boson exchange model for the exclusive process $pp \rightarrow \bar{p}ppp$.

**Fig. 3:** a) The Lorentz invariant differential cross section $E\, d^3\sigma/dp^3$ in (mb $c^3 GeV^{-2}$) at $\theta_{lab} = 0^o$ for the reaction $d + p \rightarrow \bar{p} + X$ at a deuteron momentum $P_d = 10$ GeV/c. The solid and dashed lines are the calculations with the Paris d.w.f. [24] using the parametrization of the elementary cross section from [17] and eq. (8), respectively. The dashed-dotted and dotted lines are the calculations with the Paris d.w.f. and a 3% admixture of a non-nucleonic component [13] using the parametrization from [17] and eq. (8), respectively.
b) Lorentz invariant differential cross section within the same units and notations as in a) for the reaction $dd \rightarrow \bar{p}X$ at $P_d$= 7 GeV/c.

**Fig. 4:** Ratio of Lorentz invariant antiproton spectra at $\theta_{lab} = 0^0$ from $d + d$ and $d + p$ reactions at $P_d$ =9.5 GeV/c for the Paris d.w.f. (dashed line) and the sum of the contribution from the Paris d.w.f. and a 3% admixture of a non-nucleonic component according to ref. [13].

$Ed^3\sigma/d^3p \ (mb \ GeV^{-2} \ c^3)$

$P_d = 10 \ GeV/c$

a)

d + p

$p_p \ (GeV/c)$

$P_d = 7 \ GeV/c$

d + d

b)

$p_p \ (GeV/c)$

2